Stability of Relativistic Jets from Rotating, Accreting Black Holes via Fully Three-Dimensional Magnetohydrodynamic Simulations

Jonathan C. McKinney,[1][2]* Roger D. Blandford[1]*

[1]*Department of Physics and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305-4060, USA*
[2]*Chandra Fellow*

ABSTRACT

Rotating magnetized compact objects and their accretion discs can generate strong toroidal magnetic fields driving highly magnetized plasmas into relativistic jets. Of significant concern, however, has been that a strong toroidal field in the jet should be highly unstable to the non-axisymmetric helical kink (screw) $m = 1$ mode leading to rapid disruption. In addition, a recent concern has been that the jet formation process itself may be unstable due to the accretion of non-dipolar magnetic fields. We describe large-scale fully three-dimensional global general relativistic magnetohydrodynamic simulations of rapidly rotating, accreting black holes producing jets. We study both the stability of the jet as it propagates and the stability of the jet formation process during accretion of dipolar and quadrupolar fields. For our dipolar model, despite strong non-axisymmetric disc turbulence, the jet reaches Lorentz factors of $\Gamma \sim 10$ with opening half-angle $\theta_j \sim 5°$ at 10^3 gravitational radii without significant disruption or dissipation with only mild substructure dominated by the $m = 1$ mode. On the contrary, our quadrupolar model does not produce a steady relativistic ($\Gamma \gtrsim 3$) jet due to mass-loading of the polar regions caused by unstable polar fields. Thus, if produced, relativistic jets are roughly stable structures and may reach up to an external shock with strong magnetic fields. We discuss the astrophysical implications of the accreted magnetic geometry playing such a significant role in relativistic jet formation, and we outline avenues for future work.

Key words: accretion discs, black hole physics, galaxies: jets, gamma rays: bursts, MHD, instabilities, relativity, methods: numerical

1 INTRODUCTION

Astrophysical jets were discovered by Heber Curtis in 1917, who described M87's jet as "a curious straight ray ... connected with the nucleus" (Curtis 1918). The M87 jet is the most well-studied of all jets associated with active galactic nuclei (AGN) (e.g. Baade & Minkowski 1954; Blandford & Konigl 1979a; Röser & Meisenheimer 1993). M87's jet structure has been observed down to tens of gravitational radii of the putative black hole (BH) (e.g. Junor et al. 1999; Kovalev et al. 2007; Ly et al. 2007) with impressive animations created (Walker et al. 2008). Jets have now also been observed in many other AGN/blazars (Bridle & Perley 1984), in neutron star and BH x-ray binaries (Mirabel & Rodríguez 1999; Fender et al. 2004), in Herbig-Haro objects (e.g. Konigl 1982), and are required for gamma-ray bursts (GRBs) (e.g. Piran 2005). Challenges include explaining the jet formation process, the stability of jet formation and jet propagation, how jets accelerate and collimate, and how jets obtain their composition and substructure both near and far from the central object. Jet studies are complicated by the system's environment, such as how a jet must drill through a massive envelope in the collapsar model, while FRII jets extend up to hot spots. For quasar systems, jets play an important role in limiting BH mass growth (e.g. Di Matteo et al. 2005) and driving hot bubbles that limit cooling flows (e.g. McNamara et al. 2005). However, the efficiency of the energy-momentum transfer remains unknown and probably depends on jet structure and stability.

The most universally applicable jet paradigm involves some form of magnetic-driving with strong toroidal fields that form, accelerate, and (internally) collimate jets via magnetized accretion discs (Lynden-Bell 1969; Blandford & Rees 1974; Lovelace 1976; Blandford & Payne 1982) or accreting, rotating BHs (Blandford & Znajek 1977, BZ). This paradigm was bolstered by the realization that accretion can be driven by magnetorotational turbulence generating a strong magnetic field (Balbus & Hawley 1998). Especially if discs are thick near BHs, then stronger jets and winds are driven by either stronger turbulent magnetic fields for the otherwise same mass accretion rate (e.g. Meier 2001; Miller et al. 2006) or by large-scale fields advected from large radii (see §3 & §4 in Livio et al. 1999). A magnetic field may preserve jet com-

* E-mail: jmckinne@stanford.edu (JCM); rdb3@stanford.edu (RDB);

position against entrainment (Rosen et al. 1999). The variations in magnetic field strength and BH spin may explain the diversity of jet systems like FRI/FRII's (Meier 1999), although rotation measures imply unexpected field orientations (Zavala & Taylor 2005) and simple models of decelerating jets fit FRIs (e.g. Laing et al. 2006). Soltan efficiency (and other) arguments suggest quasars contain BHs that are rapidly spinning (e.g. Gammie et al. 2004) and maybe maximally spinning (e.g. Allen et al. 2006). The intrinsic interest (and cosmological importance) of jets motivates testing whether the magnetic paradigm can explain their observed structure and stability.

Now roughly 90 years after Heber Curtis's discovery, the *straightness* of many observed jets remains as their most inexplicable feature given, e.g., fusion devices show strong toroidal fields are violently unstable to helical kink (screw) modes (e.g. Bateman 1978). Astrophysical jet stability research has revealed a large number of modes (e.g. Kadomtsev 1966) that can be unstable including "reflection" resonant modes (Payne & Cohn 1985), Kelvin-Helmholtz (KH) modes (e.g. Ferrari et al. 1978 and references therein), and current-driven modes (Benford 1981). With perturbations of the form $e^{i(m\phi+nz+lR-\omega t)}$, a nearly universal result from these simplified models is that the $m = 1$ kink mode is the most dangerous mode that could result in complete disruption and dissipation.

Even if simplified jet models are kink mode unstable, they may be stabilized by introducing gradual shear (e.g. Mizuno et al. 2007 and references therein), an external wind (Hardee & Hughes 2003), sideways expansion (Rosen & Hardee 2000), and relativistic bulk motion. For some AGN jets, observations support a lack of significant dissipation during propagation (Sambruna et al. 2006). If unstable, however, jets can be a source of heating, radiation, and high-energy particles due to shocks (e.g. Blandford & Konigl 1979a), reconnection (e.g. Drenkhahn & Spruit 2002; Lyutikov 2006; Giannios & Spruit 2006), viscous shear, turbulent cascade (e.g. Begelman 1998), and a break-down of the ideal single-component fluid approximation (Trussoni et al. 1988).

For magnetized jets, the current-driven screw ($n > 0, m = 1$) mode is potentially most disruptive. For cylindrical force-free equilibria one obtains the Kruskal-Shafranov (KS) instability criterion

$$-\frac{B^\phi}{B^p} > \frac{2\pi R}{r}, \tag{1}$$

where B^ϕ and B^p are the toroidal and poloidal field strengths, $R = r\sin\theta$ is cylindrical radius, and r is poloidal extent. This suggests jets are unstable beyond the Alfvén surface where $B^\phi \gtrsim B^p$ and $r \gtrsim R$, located at only $r \lesssim 10M$ (in this Letter, $G \equiv c \equiv 1$) for rotating BHs or accretion discs. The KS criterion implies jets go unstable before accelerating to relativistic ($\Gamma \gtrsim 3$) speeds as likely only after $r \sim 100M$ (McKinney 2006a), and the KS criterion probably cannot explain some FRIIs extending to $r \sim 10^7 M$.

Advanced linear stability analyses from normal mode and extremal energy arguments for simplified cylindrical jets are often based upon restrictive assumptions, which has lead researchers to suggest that jets are violently unstable (Begelman 1998; Lyubarskii 1999; Li 2000), mildly unstable (e.g. Lery et al. 2000), or even stable (e.g. Istomin & Pariev 1996) to the screw mode. Tomimatsu et al. (2001) found that relativistic field rotation of freely expanding solutions (McKinney 2006a,c; Narayan et al. 2007) allows jets to be unstable only if *both* the KS criterion and their criterion,

$$-\frac{B^\phi}{B^p} > \frac{R\Omega_F}{c}, \tag{2}$$

are satisfied, where Ω_F is the field line rotation frequency and c is the speed of light. This implies jets are marginally stable until a strong external medium interaction. Their analysis is suggestive, but it only strictly applies inside, not through, the Alfvén surface. So far, no sufficiently general analytical screw stability analysis has been performed for magnetically-dominated relativistic jets.

Analytical approaches become intractable for more realistic jets. It remains difficult to compare theory with observations (e.g. Worrall et al. 2007) and laboratory experiments (e.g. Ciardi et al. 2008). Primarily, numerical magnetohydrodynamical (MHD) simulations have proven useful to study realistic jet models. Simulations range from injecting an arbitrary jet from a surface inlet (e.g. Nakamura & Meier 2004; Zhang et al. 2004; Leismann et al. 2005; Komissarov et al. 2008; Moll et al. 2008) to injecting a jet from an unresolved Keplerian disc (e.g., Tchekhovskoy et al. 2008), and to evolving both the disc and jet (e.g., Hawley et al. 2001; McKinney & Gammie 2002, 2004; Kigure & Shibata 2005; McKinney 2005; Hawley & Krolik 2006; McKinney 2006a; McKinney & Narayan 2007a,b; Komissarov & McKinney 2007). Advanced 3D MHD simulations that inject jets from an inlet find that KH kink modes are stabilized by sheaths around the jets (Mizuno et al. 2007) and that even non-relativistic screw modes saturate before causing magnetic dissipation (Moll et al. 2008). More realistic simulations are crucial since analytical experience suggests free parameters in jet-injection simulations probably play a significant role. In particular, only global simulations allow a stability study of the actual jet formation process in the presence of disc turbulence and different global field geometries. Accretion of small quadrupolar field loops was already shown to degrade the jet (McKinney & Gammie 2004; Beckwith et al. 2008), but this could be due to their choice of starting with small field loops in the disc with numerical dissipation not allowing the development of a large-scale quadrupolar field.

2   NUMERICAL MODEL

We perform fully 3D global general relativistic MHD (GRMHD) simulations starting with an equilibrium matter torus, whose angular momentum is aligned with the BH (Kerr metric) spin. To facilitate comparisons, we follow McKinney (2006a) and choose a torus pressure maximum at $r = 12M$, inner edge at $r = 6M$, and adiabatic index $\gamma = 4/3$ giving disc thickness $\delta\theta \sim \pm 0.3$. For BH spins of $a/M \gtrsim 0.4$, simulations of such tori are qualitatively similar (McKinney & Gammie 2004). We choose all models to have $a/M = 0.92$ (hole angular frequency, $\Omega_H = a/(2Mr_+) \approx 0.33M^{-1}$, with horizon radius, r_+) such that the BH is in spin equilibrium for our disc thickness (Gammie et al. 2004). We use the conservative unsplit 3D GRMHD code HARM (Gammie et al. 2003), Kerr-Schild coordinates, 4th-order interpolation and 4th-order Runge-Kutta (McKinney 2006a), a robust inversion scheme (Mignone & McKinney 2007), a staggered field scheme (McKinney et al., in prep.), and other advances (McKinney 2006b; Tchekhovskoy et al. 2007).

We consider both dipolar and quadrupolar field geometries. The dipolar model starts with a single field loop within the torus as in McKinney (2006a). Dipolar models correspond to the most-often simulated jet (or jet+disc) model were the current sheet is assumed to be at (or develops near) the equator. To give the quadrupole geometry the best chance of producing a jet, we study a *large-scale* quadrupolar field with vector potential ϕ component

$$A_{\text{quadrupole}} = A_{\text{dipole}}\cos\theta, \tag{3}$$

using a paraboloidal-like potential given by

$$A_{\mathrm{dipole}} = (1/2)[(r + r_0)^\nu f_- + 2M f_+ (1 - \ln(f_+))], \qquad (4)$$

where $f_- = 1 - \cos^\mu \theta$, $f_+ = 1 + \cos^\mu \theta$, $\nu = 3/4$, $\mu = 4$, $r_0 = 4$, and applies for $\theta < \pi/2$ and for $\theta > \pi/2$ when letting $\theta \to \pi - \theta$. In this model, current sheets form above and below the equator. From prior GRMHD simulations, we expect primarily the initial field's multipole order to be important, and particular model parameter values should be unimportant once a quasi-steady state is reached. All models have initial gas pressure per unit magnetic pressure of ≈ 100 at the equator in the disc. We allow the comoving magnetic energy per rest-mass energy up to only 100 during mass evacuation near the BH (see floor model in McKinney 2006a).

Spherical polar, not Cartesian, coordinates are used since preferred for rotating jets. Our fiducial models have resolution $256 \times 128 \times 32$ in $r \times \theta \times \phi$, with non-uniform grid as in McKinney (2006a), except $R_0 = 0$ and $n_r = 1$ in their equation (18). Based upon code tests, our 2nd-order monotonized central limiter scheme would require roughly $4\times$ the per-dimension resolution to obtain the accuracy our 4th-order scheme by the end of the simulation. Unlike prior 3D GRMHD simulations, the grid warps to resolve the disc at small radii and follows the collimating jet at large radii giving roughly $3\times$ more angular resolution at large radii. Hence, compared to any scheme similar to the original 2nd-order HARM scheme, our effective resolution is roughly $1024 \times 1536 \times 128$. Unlike most 3D GRMHD simulations (e.g. Beckwith et al. 2008), we include the full $\Delta\phi = 2\pi$ extent as required to resolve the $m = 1$ mode and include the full $\Delta\theta = \pi$ extent (no cut-out at poles). As Fragile et al. (2007), we use transmissive (not reflecting) polar boundary conditions. As they state, the singularity need not be treated specially for centered quantities in a finite-volume scheme. Our field is staggered, and the polar value of B^θ is evolved by using the analytical limit of the finite volume induction equation at the pole such that angular-dependent area factors cancel (McKinney et al., in prep.). Coordinate directions twist at the pole leading to some dissipation, but this is significantly reduced by our 4th-order scheme that well-resolves up to $m = 4$ with 32 ϕ cells. At the inner torus edge, cells have aspect ratio 1:5:10 and the fastest-growing magnetorotational mode is resolved with 6 cells, as sufficient (Shafee et al. 2008). We also studied resolutions of $128 \times 128 \times 32$, $128 \times 64 \times 32$, and $128 \times 64 \times 16$; the jet's Fourier $m = 1, 2, 3$ power is converged to 20%. Using 128 angular cells and staggered field scheme were required for MHD jet invariants to be conserved to $\lesssim 10\%$, which is evidence of an accurate solution (Tchekhovskoy et al. 2008).

Most disc+jet simulations do not evolve to large enough radii to resolve a highly relativistic jet. For magnetically-dominated paraboloidal jets, the maximum Lorentz factor at large radii is

$$\Gamma \approx 0.3 \left(\frac{r}{M} \right)^{0.5}, \qquad (5)$$

(Tchekhovskoy et al. 2008). We choose an outer box radius of $10^3 M$ as required to reach $\Gamma \sim 10$. All simulations ran a duration of $5000M$, which is 192 orbits at the inner-most stable circular orbit (ISCO) ($r_{\mathrm{ISCO}} \approx 2.2M$) and 50 orbits at the initial inner torus edge. The accretion rate of mass ($\dot{M}$), energy, and angular momentum are roughly constant with radius out to $r \sim 10M$ by $t \sim 3000M$, indicating the disc has reached a quasi-steady state. The slow/contact modes for the jet move with $v/c \gtrsim 0.2$, so the jet is beyond the box by $t = 5000M$. We report many results at $t \sim 4000M$ since this is before the jet partially reflects off the outer box.
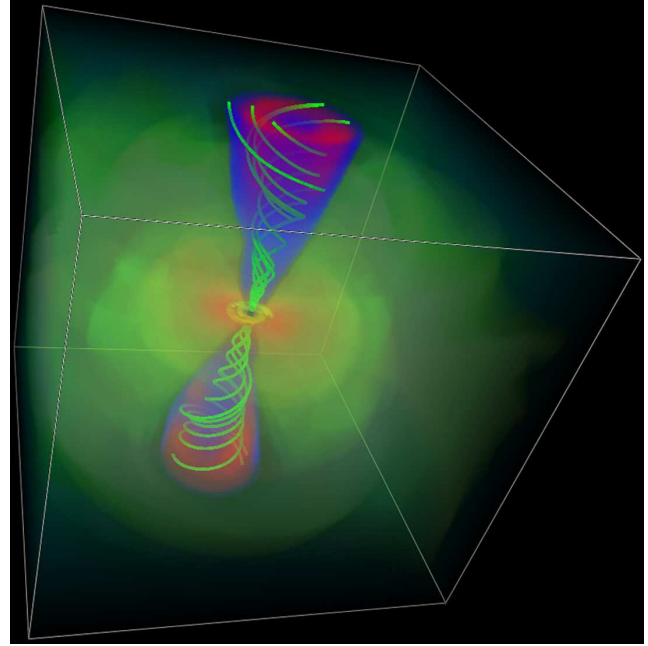
Figure 1. For dipolar model, shows inner $\pm 100M$ cubical region with BH, accretion disc (pressure, yellow isosurface), outer disc and wind (log rest-mass density, low green, high orange, volume rendering), relativistic jet (Lorentz factor of $\Gamma \lesssim 4$, low blue, high red, volume rendering), and magnetic field lines (green) threading BH. Despite non-axisymmetric turbulence, polar magnetically-dominated jets are launched by the BZ effect.

3 RESULTS

The fiducial dipole model is overall similar to prior 2D simulations (McKinney & Gammie 2004; McKinney 2006a). The BH-driven polar jet survives in a non-dissipated state to large radii. Each polar, magnetically-dominated jet at $r_+, 10, 10^2, 10^3 M$ has constant electromagnetic luminosity of $L_j \approx 0.01\dot{M}c^2$, with only a small secular drop as Γ increases. This value is similar to higher resolution 2D simulations (McKinney & Gammie 2004). The total (disc+jet+wind) electromagnetic output peaks at $r \approx 10M$, but disc power is dissipated so does not survive at large radii (McKinney & Narayan 2007a). Figure (1) shows the inner $\pm 100M$ cubical region and Figure (2) shows out to $z = 10^3 M$ by $t = 4000M$. The figures show the disc wind and relativistic jet generated by the rotating BH and magnetized, turbulent accretion disc. The jet is roughly stable out to $z = 10^3 M$ reaching $\Gamma \sim 5 - 10$. Figure (2) shows the kinked polar jet structure of the poloidal current, RB^ϕ, capable of driving screw instabilities. We measure the Fourier power within the jet region defined by magnetic energy per rest-mass energy, averaged for all ϕ, greater than one. At large distances the $m = 1, 2, 3, 4$ powers relative to $m = 0$ are 7%, 1%, 0.7%, 0.6% in magnetic energy, 6%, 4%, 0.5%, 0.2% in Lorentz factor, roughly 37%, 7%, 3%, 4% in both rest-mass density (ρ_0) and RB^ϕ, and 20%, 13%, 7%, 6% in internal energy density. Both ρ_0 and RB^ϕ reach $m = 1$ power of 100% in the jet next to the outer disc edge at $r = 20M$. There is no indication of growth beyond perturbations induced by the disc turbulence, which appears to be the primary origin of jet substructure.

Now we discuss our fiducial large-scale quadrupole model. GRMHD simulations show that no strong jet emerges due to the accretion of higher multipole moments put initially within the disc (McKinney & Gammie 2004; McKinney & Narayan 2007a,b;
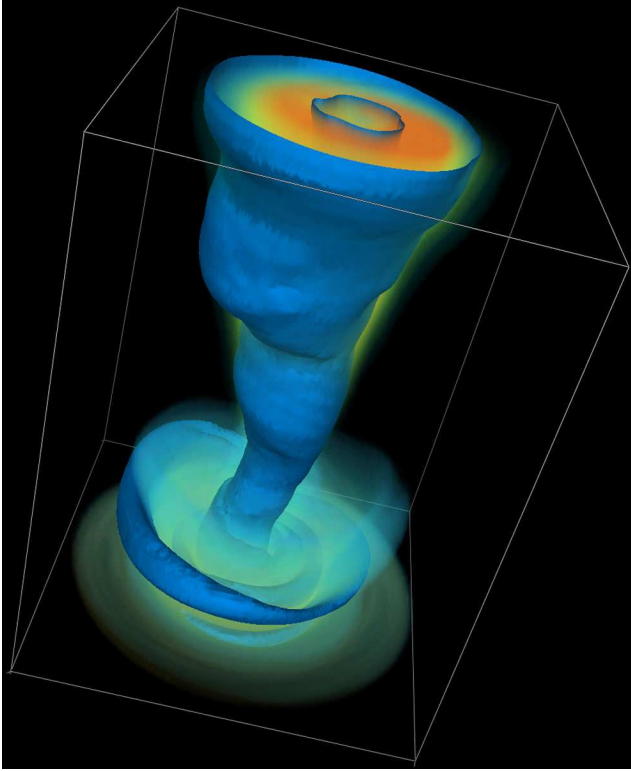
Figure 2. For dipolar model, shows accreting BH generating relativistic jet (only one side shown) vertically out to $10^3 M$ within $\theta \approx \pm 20°$ ($350M \times 350M$) at $t = 4000M$. Shown are outskirts of disc and wind (log internal energy density, cyan volume rendering), outer/inner boundary of perturbed jet and fragments of disc wind (RB^ϕ, blue isosurface), and relativistic jet (Lorentz factor of $\Gamma \lesssim 10$, orange volume rendering) collimated within half-angle $\theta_j \approx 5°$. Despite perturbations, the jet is a stable structure.

Beckwith et al. 2008). In our fully 3D simulations, even putting in an initial large-scale quadrupolar field leads to no strong jet once equatorial symmetry is broken by $t \sim 2500M$. While the polar field strength is similar to that in the dipole model when the field threads the horizon, the polar regions are mass-loaded when tearing coronal current sheets eject polar field to slightly larger radii. Then, magnetic pressure no longer balances against the low angular momentum disc material that moves into the polar region. The coronal-polar field is accreted and ejected throughout the simulation, which leaves no time allowed for the funnel to drain. This leads to order unity magnetic energy and internal energy per particle rest-mass energy, which is insufficient to generate a highly relativistic ($\Gamma \gtrsim 3$) jet. Similar results by Beckwith et al. (2008) using a non-energy-conserving code suggest detailed thermodynamics do not control this process. At late times, (total and polar) BH electromagnetic power are negative. The polar regions have both inflows and outflows, and there is only a disc-mass-loaded wind with an electromagnetic power output per pole at large radii of $L_w \approx 0.002 \dot{M} c^2$, which is significantly less powerful than the dipole model. Similar as the disc wind in the dipolar model, the outflow has a weak disorganized poloidal field and a more organized toroidal field stronger by factors of typically $10 - 40$ both near the BH and at large radii. Corresponding 2D simulations show less drastic, but comparable, degradation of the jet. A thinner disc may not allow as much mass-transfer to the poles, but thinner discs have weaker turbulent fields and inward advection of strong ordered field may not be possible

for thin discs. Also, higher resolutions may lead to less vigorous reconnection or may show a more narrow, polar jet still emerges.

4 DISCUSSION

We have performed fully 3D global GRMHD simulations of accreting, rapidly rotating BHs and found that dipolar fields near BHs can launch magnetically-dominated, relativistic ($\Gamma \gtrsim 3$) jets that survive to $10^3 M$ without significant disruption or measurable dissipation. Disc turbulence appears to be the primary cause of jet substructure that is dominated by the $m = 1$ mode, which has no measurable growth within the jet. Prior work applying a form of the Kruskal-Shafranov criterion (solution for non-relativistic, cylindrical equilibria) to highly magnetized relativistic flows (e.g. Lyutikov 2006; Giannios & Spruit 2006), needs to be reevaluated to consider the stabilizing effects of field rotation, gradual shear, a surrounding sheath, and sideways expansion as present in the simulations. Unlike dipolar fields, quadrupolar fields near BHs lead to only weak, turbulent outflows and negligible magnetically-dominated polar regions and no relativistic ($\Gamma \gtrsim 3$) jets. Since our simulations with relativistic jets have no current sheets within the jet, reconnection may not be an important source of dissipation unlike assumed by some models (e.g. Drenkhahn & Spruit 2002.)

These and prior GRMHD simulation results suggest that a rotating ($a/M \gtrsim 0.4$) BH is a necessary, but not sufficient, condition to produce a highly relativistic ($\Gamma \gtrsim 3$) jet. In addition, one requires the accreted magnetic field to be mostly dipolar, rather than higher-order, so a dipolar field threads the region near the BH (see also Narayan et al. 2003). This might explain various observations, such as the dichotomy of FRI and FRII systems. FRI's are found in rich clusters, are two-sided so weakly relativistic, and have dissipative emission near the core. FRII's are found in poor groups or isolated, are one-sided so more relativistic, are more powerful, and dissipate little till the radio lobe (Owen & Ledlow 1994). The FRI/FRII dichotomy may then be due to the complexity of the environment (e.g. through hierarchical merging) controlling the field multipole structure. Then, FRII systems are primarily BH-driven able to pierce through an ambient medium, while FRI systems are those mostly driven by the broader, dissipative, magnetically-disordered disc wind with $\Gamma \lesssim 3$ that one expects to be more easily entrained, slowed, and disrupted, as consistent with observations (Laing et al. 2006). Radial structure (e.g. arcs and knots) could be due to accretion switching between dipolar and higher-order multipoles. For M87, there could be a dark or boosted relativistic spine with the slower, dissipative disc wind producing emission on scales within several parsecs (Kovalev et al. 2007). For SrgA*, no jet may emerge because of accretion from various stellar clusters generating a dominant non-dipolar field (Nayakshin et al. 2007). For x-ray binaries, jets in the low-hard states could be driven by dipolar fields that could even accumulate to the point of lowering accretion rates (Igumenshchev et al. 2003), intermediate to soft states could involve higher-order multipole moments, and transient jets from the hard-to-soft transitions could occur due to dissipation of the dipolar component. For GRBs, the BH-disc system may be required to be highly symmetric to maintain a strong dipolar field to produce an ultrarelativistic jet. That ordered poloidal field must be accreted assumes no dynamo exists for generating a baryon-pure, large-scale poloidal field from disorganized field (Beckwith et al. 2008).

Future jet studies should consider the effects of much higher resolutions, misaligned BH-disc accretion (since misaligned systems may more readily produce non-dipolar fields), larger radii of

$10^7 M$ for AGN and $10^{12} M$ for GRBs (to determine very large-scale stability and to obtain larger Γ), resistivity and viscosity, disc radial extent (that limits the terminal Lorentz factor since the lack of the disc and supportive disc wind allows the jet to become monopolar and so accelerate inefficiently), disc thickness (that can control the strength of turbulent or advected field), other magnetic field geometries (including with non-zero net helicity), BH spin (especially very low and very high), cooling (such as neutrino cooling in collapsar discs), and the presence of an extended massive envelope as in the collapsar model (freely expanding outflows simulated here apply to a late phase after the jet drills through the envelope). Future studies should also do a quantitative analysis of the modes within the jet to identify which mode types are present. The simulated jet can be used as a well-motivated background state for future linear perturbation analyses, parameter searches, and synchrotron and inverse Compton maps for, e.g., VLBI, Chandra, and Fermi.

ACKNOWLEDGMENTS

REFERENCES

Allen, S. W. et al. 2006, MNRAS, 372, 21
Baade, W., & Minkowski, R. 1954, ApJ, 119, 215
Balbus, S. A., & Hawley, J. F. 1998, Rev. Mod. Phys., 70, 1
Bateman, G. 1978, MHD Instabilities, MIT Press, Cambridge Mass.
Beckwith, K., Hawley, J. F., & Krolik, J. H. 2008, ApJ, 678, 1180
Begelman, M. C. 1998, ApJ, 493, 291
Benford, G. 1981, ApJ, 247, 792
Blandford, R. D., & Rees, M. J. 1974, MNRAS, 169, 395
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Blandford, R. D., & Konigl, A. 1979a, Astrophys. Lett., 20, 15
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Bridle, A. H., & Perley, R. A. 1984, ARA&A, 22, 319
Ciardi, A., et al. 2008, arXiv:0811.2736
Curtis, H. D. 1918, Pub. Lick Obs., 13, 31
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Drenkhahn, G., & Spruit, H. C. 2002, A&A, 391, 1141
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
Ferrari, A., Trussoni, E., & Zaninetti, L. 1978, A&A, 64, 43
Fragile, P. C., Blaes, O. M., Anninos, P., & Salmonson, J. D. 2007, ApJ, 668, 417
Gammie, C. F., McKinney, J. C., & Tóth, G. 2003, ApJ, 589, 444
Gammie, C. F., Shapiro, S. L., & McKinney, J. C. 2004, ApJ, 602, 312
Giannios, D., & Spruit, H. C. 2006, A&A, 450, 887
Hardee, P. E., & Hughes, P. A. 2003, ApJ, 583, 116
Hawley, J. F., Balbus, S. A., & Stone, J. M. 2001, ApJ, 554, L49
Hawley, J. F., & Krolik, J. H. 2006, ApJ, 641, 103
Igumenshchev, I. V., Narayan, R., & Abramowicz, M. A. 2003, ApJ, 592, 1042

Istomin, Y. N., & Pariev, V. I. 1996, MNRAS, 281, 1
Junor, W., Biretta, J. A., & Livio, M. 1999, Nature, 401, 891
Kadomtsev, B. B. 1966, Rev. Plasma Phys., 2, 153
Kigure, H., & Shibata, K. 2005, ApJ, 634, 879
Komissarov, S. S., & McKinney, J. C. 2007, MNRAS, 377, L49
Komissarov, S., Vlahakis, N., Konigl, A., & Barkov, M. 2008, arXiv:0811.1467
Konigl, A. 1982, ApJ, 261, 115
Kovalev, Y. Y., Lister, M. L., Homan, D. C., & Kellermann, K. I. 2007, ApJ, 668, L27
Laing, R. A., Canvin, J. R., Bridle, A. H., & Hardcastle, M. J. 2006, MNRAS, 372, 510
Leismann, T. et al. 2005, A&A, 436, 503
Li, L.-X. 2000, ApJ, 531, L111
Lery, T., Baty, H., & Appl, S. 2000, A&A, 355, 1201
Livio, M., Ogilvie, G. I., & Pringle, J. E. 1999, ApJ, 512, 100
Lovelace, R. V. E. 1976, Nature, 262, 649
Ly, C., Walker, R. C., & Junor, W. 2007, ApJ, 660, 200
Lynden-Bell, D. 1969, Nature, 223, 690
Lyutikov, M. 2006, New J. of Phys., 8, 119
Lyubarskii, Y. E. 1999, MNRAS, 308, 1006
McNamara, B. R. et al. 2005, Nature, 433, 45
McKinney, J. C., & Gammie, C. F. 2002, ApJ, 573, 728
McKinney, J. C., & Gammie, C. F. 2004, ApJ, 611, 977
McKinney, J. C. 2005, ApJ, 630, L5
McKinney, J. C. 2006a, MNRAS, 368, 1561
McKinney, J. C. 2006b, MNRAS, 367, 1797
McKinney, J. C. 2006c, MNRAS, 368, L30
McKinney, J. C., & Narayan, R. 2007a, MNRAS, 375, 513
McKinney, J. C., & Narayan, R. 2007b, MNRAS, 375, 531
Meier, D. L. 1999, ApJ, 522, 753
Meier, D. L. 2001, ApJ, 548, L9
Mignone, A., & McKinney, J. C. 2007, MNRAS, 378, 1118
Miller, J. M. et al. 2006, ApJ, 653, 525
Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409
Mizuno, Y., Hardee, P., & Nishikawa, K.-I. 2007, ApJ, 662, 835
Moll, R., Spruit, H. C., & Obergaulinger, M. 2008, arXiv:0809.3165
Nakamura, M., & Meier, D. L. 2004, ApJ, 617, 123
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2003, PASJ, 55, L69
Narayan, R., McKinney, J. C., & Farmer, A. J. 2007, MNRAS, 375, 548
Nayakshin, S., Cuadra, J., & Springel, V. 2007, MNRAS, 379, 21
Owen, F. N., & Ledlow, M. J. 1994, The Physics of Active Galaxies, 54, 319
Payne, D. G., & Cohn, H. 1985, ApJ, 291, 655
Piran, T. 2005, Reviews of Modern Physics, 76, 1143
Rosen, A., Hardee, P. E., Clarke, D. A., & Johnson, A. 1999, ApJ, 510, 136
Rosen, A., & Hardee, P. E. 2000, ApJ, 542, 750
Röser, H.-J., & Meisenheimer, K. 1993, Jets in Extragalactic Radio Sources, 421,
Shafee, R., McKinney, J. C., Narayan, R., Tchekhovskoy, A., Gammie, C. F., & McClintock, J. E. 2008, ApJ, 687, L25
Sambruna, R. M., Gliozzi, M., Tavecchio, F., Maraschi, L., & Foschini, L. 2006, ApJ, 652, 146
Tchekhovskoy, A., McKinney, J. C., & Narayan, R. 2007, MNRAS, 379, 469
Tchekhovskoy, A., McKinney, J. C., & Narayan, R. 2008, MNRAS, 388, 551

Tomimatsu, A., Matsuoka, T., & Takahashi, M. 2001, Phys. Rev. D, 64, 123003

Trussoni, E., Massaglia, S., Bodo, G., & Ferrari, A. 1988, MN-RAS, 234, 539

Walker, R. C., Ly, C., Junor, W., & Hardee, P. J. 2008, Journal of Physics Conference Series, 131, 012053

Worrall, D. M., et al. 2007, MNRAS, 380, 2

Zavala, R. T., & Taylor, G. B. 2005, ApJ, 626, L73

Zhang, W., Woosley, S. E., & Heger, A. 2004, ApJ, 608, 365